

Radiance Temperature (at 653 nm) of Iron at Its Melting Point

A. Cezairliyan and J. L. McClure

Institute for Materials Research, National Bureau of Standards, Washington, D.C. 20234

(April 21, 1975)

Radiance temperature (at 653nm) of iron at its melting point was measured using a subsecond-duration pulse heating technique. Specimens in the form of strips with initially different surface roughnesses were used. The results do not indicate any dependence of radiance temperature (at the melting point) on initial surface or system operational conditions. The average radiance temperature (at 653 nm) at the melting point for 13 specimens is 1670 K on IPTS-68, with a standard deviation of 0.8 K and a maximum absolute deviation of 1.7 K. The total error in the radiance temperature is estimated to be not more than ± 6 K.

Key words: High-speed measurements; high temperature; iron; melting; normal spectral emittance; radiance temperature.

1. Introduction

A subsecond-duration pulse heating technique was used earlier to measure the radiance temperature¹ of niobium [1],² zirconium [2], and molybdenum [3] at their respective melting points. It was found that the radiance temperature was constant during the initial melting period and was reproducible for different specimens of the same substance. In the present study, the same technique is used to measure the radiance temperature of iron at its melting point.

The method is based on rapid resistive self-heating of the specimen from room temperature to its melting point in less than one second by the passage of an electrical current pulse through it; and on measuring specimen radiance temperature (at the rate of 1200 temperatures per second) with a high-speed photoelectric pyrometer [4]. The radiance measurements were performed at 653 nm which corresponds to the effective wavelength of the pyrometer's interference filter. The bandwidth of the filter was 10 nm. The circular area viewed by the pyrometer was 0.2 mm in diameter. Details regarding the construction and operation of the measurement system are given in earlier publications [5, 6].

2. Measurements

The measurements of the radiance temperature (at 653 nm) of iron (99.95% pure) at its melting point were performed on 13 specimens in the form of strips. The

manufacturer's typical analysis indicated the presence of the following impurities in ppm by weight: O, 34; C, 30; Na, 10; P, 20; S, 30; Cr, 30; Co, 100; Ni, 150. The total amount of all other detected elements was less than 60 ppm, each element being below 10 ppm limit. The nominal dimensions of the strips were: length, 51 mm; width, 3.2 mm and thickness, 0.25 mm. Before the experiments, specimen surface was treated using abrasive; three different grades of abrasive were used yielding three different surface roughnesses (ranging from approximately 0.2 to 0.5 μm in RMS value) for different specimens. In some experiments, specimens with "as received" surface conditions (approximately 0.1 μm in roughness) were also used. Heat treatment was applied to one of the specimens prior to melting by pulse heating it to approximately 1500 K for ten times. At the end of this procedure, the specimen surface showed rough irregularities which resulted from going through the $\alpha \rightarrow \gamma$ crystallographic transformation.

All the experiments were performed with the specimen in an argon environment at atmospheric pressure. The heating rate for different specimens was in the range $1200 \text{ K} \cdot \text{s}^{-1}$ to $4300 \text{ K} \cdot \text{s}^{-1}$, corresponding to specimen heating periods (from room temperature to its melting point) in the range 0.15 to 0.5 s.

Radiance temperature of iron at its melting point for the 13 specimens and other pertinent results are reported in table 1. All temperatures reported in this paper are based on the International Practical Temperature Scale of 1968 [7]. Variation of the radiance temperature as a function of time near and at the melting point is shown in figure 1 for two typical experiments representing two specimens with different initial surface and heat treatment conditions. The magnitude of the spike before the melting plateau for one of the specimens is probably related to the

¹ Radiance temperature (sometimes referred to as brightness temperature) is the apparent temperature of the specimen surface corresponding to the effective wavelength of the measuring pyrometer.

² Figures in brackets indicate the literature references at the end of this paper.

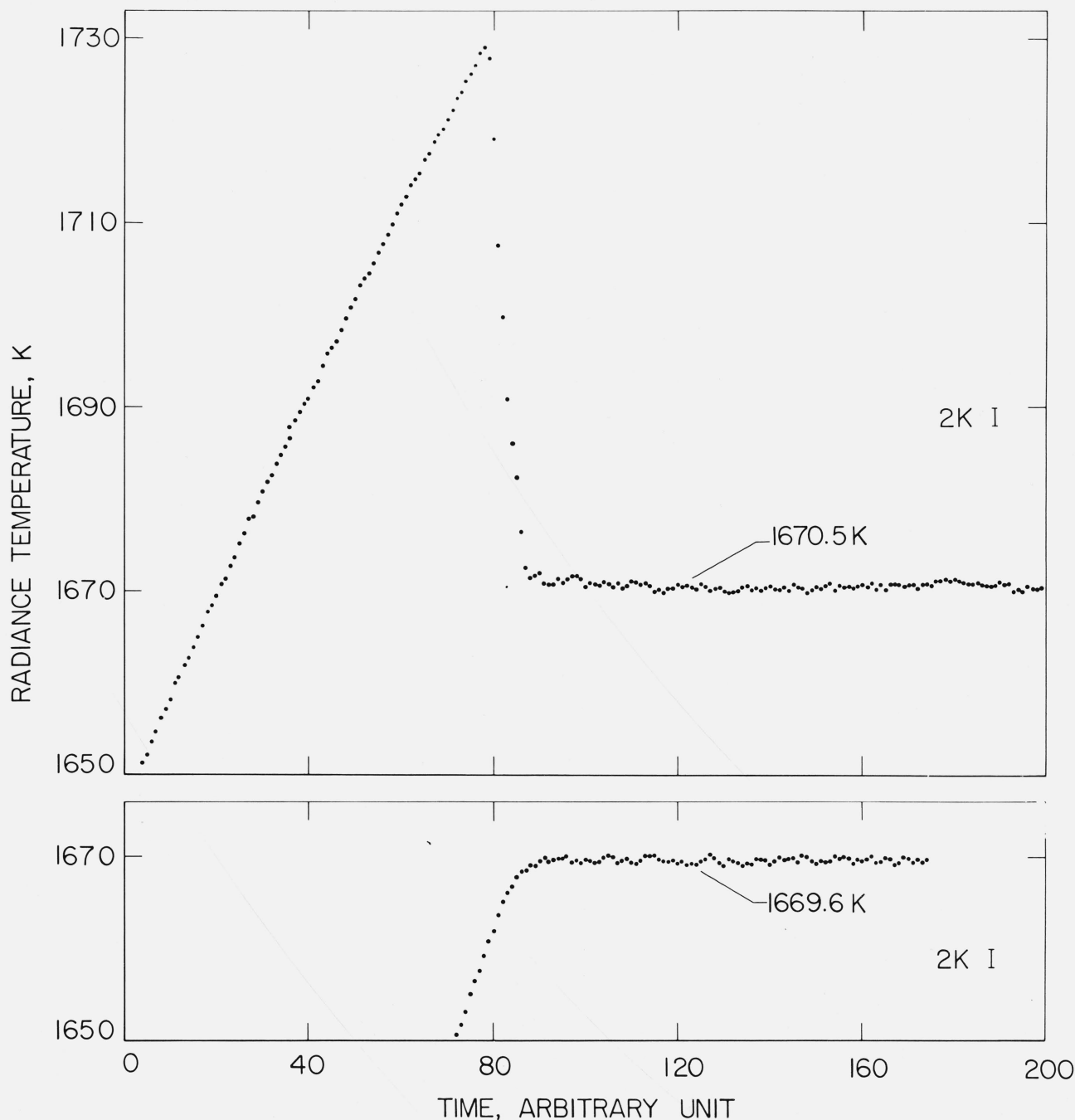


FIGURE 1. Variation of radiance temperature (at 653nm) of iron as a function of time near and at its melting point for two typical experiments (1 time unit = 0.833 ms).

The upper curve corresponds to the experiment in which the specimen (number 13) was heat treated prior to melting by pulse heating it for ten times to approximately 1500 K — above its $\alpha \rightarrow \gamma$ transformation point — which created an irregular and rough surface. The high values before the plateau are indicative of the differences in the normal spectral emittance of the solid and liquid phases. The lower curve corresponds to the experiment in which the specimen (number 3) had a smooth surface prior to melting as indicated by the absence of a spike before the plateau.

degree of initial surface roughness of the specimen. However, regardless of the differences in the initial conditions, radiance temperature at the melting plateau is approximately the same for the two specimens. It may be seen from table 1 that this argument is also satisfied by the other specimens.

A single value for the radiance temperature at the plateau for each specimen was obtained by averaging the temperatures at the plateau. The number of temperatures used for averaging ranged from 42 to 119, depending both on the melting rate and on the behavior of the specimen during melting. The standard deviation

of an individual temperature from the average was in the range 0.3 to 0.4 K for all the experiments. Similar values (for standard deviation) were obtained when fitting the temperature data corresponding to the premelting period to a quadratic function in time. This indicates that during melting no undesirable effects took place, such as vibration of the specimen, development of hot spots in the specimen and random changes in the specimen surface conditions.

To determine the trend of measured temperatures at the plateau, temperatures for each experiment were fitted to a linear function in time using the least squares method. The slopes of the linear function do not show any significant bias with respect to sign. The detailed results are reported in table 1. The temperature difference between the beginning and the end of the plateau (corresponding to the slope in the plateau) is in the range 0 to 0.4 K. The standard deviation of an individual temperature from the linear function was approximately the same as the standard deviation obtained by direct averaging of the temperatures.

The average radiance temperature at the melting point for the 13 iron specimens was 1670.3 K with a standard deviation of 0.8 K and a maximum absolute deviation of 1.7 K. The results are presented in figure 2.

A detailed analysis of the sources and magnitudes of the errors in the measurements using the present system is given in an earlier publication [5]. In a more recent publication [3], the specific errors in radiance temperature measurements are summarized. Based on these, it is estimated that the total error (random and

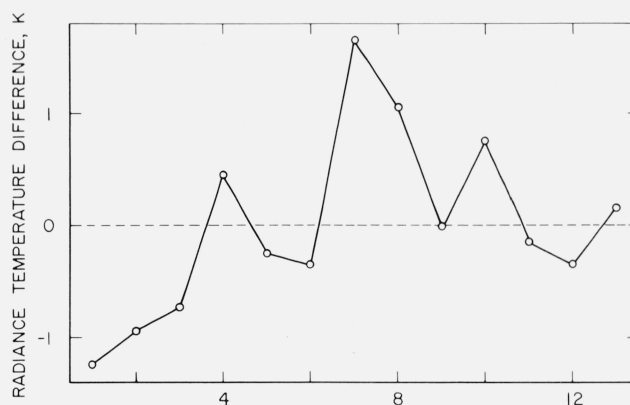


FIGURE 2. Difference of radiance temperature (at the melting point of iron, at 653 nm) for individual experiments from their average value of 1670.3 K (represented by the "zero" line).

systematic) in the radiance temperature of iron at its melting point is not more than 6 K. This includes an uncertainty of about 1 K in the melting point due to the impurities in the specimen.

It may be concluded that the radiance temperature (at 653 nm) of iron at its melting point is 1670 ± 6 K.

3. Discussion

The pulse heating technique used in this study has demonstrated the capability of measuring radiance temperature of metals during their initial melting

TABLE 1. Summary of measurements of radiance temperature (at 653 nm) of iron during melting

Specimen number ^a	Surface roughness ^b	Premelting period		Melting period				
		Heating rate ^c K · s ⁻¹	Standard deviation ^d K	Number of temperatures ^e	Slope at plateau ^f K · s ⁻¹	Plateau temp. difference ^g K	Radiance temperature ^h K	Standard deviation ⁱ K
1	B	1200	0.3	109	0	0	1669.1	0.4
2	C	1500	.4	49	3.7	0.2	1669.4	.3
3	A	1800	.4	83	0	0	1669.6	.4
4	B	2000	.3	99	3.6	0.3	1670.8	.4
5	D	1900	.3	93	-2.9	-0.2	1670.1	.4
6	A	1900	.3	44	-12.1	-0.4	1670.0	.4
7	C	1700	.3	93	0	0	1672.0	.4
8	C	2800	.4	63	-4.2	-0.2	1671.4	.4
9	B	3000	.4	56	-8.4	-0.4	1670.3	.4
10	D	3000	.4	46	7.4	0.3	1671.1	.3
11	D	4300	.3	58	9.4	0.4	1670.2	.3
12	A	4300	.4	42	-4.7	-0.2	1670.0	.3
13	E	1500	.4	119	-2.5	-0.2	1670.5	.4

^a Also represents the experiments in chronological order.

^b The notations used for surface conditions correspond to the following typical roughnesses in μm : A, 0.1; B, 0.2; C, 0.4; D, 0.5. Surface "A" designates the specimen under "as received" condition. Surface "E" designates the specimen after heat treating it to about 1500 K.

^c Heating rate evaluated at a temperature approximately 10 K below the melting point.

^d Represents standard deviation of an individual temperature as computed from the difference between the measured value and that from the smooth temperature versus time function (quadratic) obtained by the least squares method. Data extend approximately 100 K below the melting point.

^e Number of temperatures used in averaging the results at the

plateau to obtain an average value for the radiance temperature at the melting point of the specimen.

^f Derivative of the temperature versus time function obtained by fitting the temperature data at the plateau to a linear function in time using the least squares method.

^g Maximum radiance temperature difference between the beginning and the end of the plateau based on the linear temperature versus time function.

^h The average (for a specimen) of measured radiance temperatures at the plateau.

ⁱ Standard deviation of an individual temperature as computed from the difference between the measured value and that from the average plateau radiance temperature.

period. It may be noted, however, that with the present system, it was not possible to follow the entire melting process because the specimen collapsed and opened the main electrical circuit prior to the completion of melting.

The present results have shown the constancy and reproducibility of the radiance temperature of iron at its melting point for a number of specimens with different initial surface conditions. This substantiates similar earlier results on other metals: niobium [1], zirconium [2] and molybdenum [3].

Bonnell et al. [8] have reported a value of 1671 K for the radiance temperature (at 645 nm) of iron at its melting point. Since the wavelength dependence of the radiance temperature for iron at its melting point is not known, it is not possible to compare exactly the result of Bonnell et al. with that of the present work. However, an estimated value of about $0.25 \text{ K} \cdot \text{nm}^{-1}$ for the wavelength dependence of the radiance temperature obtained from an extrapolation of the lower temperature (1600 to 1800 K) results [9] adjusts the radiance temperature value from 1671 K (at 645 nm) to 1669 K (at 653 nm). This is about 1 K lower than the result of the present work.

Considering 1808 K for the melting point of iron [10] and 1670 K for the radiance temperature at the melting point, a value of 0.365 is obtained for the normal spectral emittance (at 653 nm) of iron at its melting point. The values reported in the literature are: 0.36 at 660 nm [11] and 0.37 at 650 nm [12].

In conclusion, the results of the present work in addition to earlier results on niobium, zirconium and molybdenum suggests the possibility of using the radiance temperature at the melting point of selected metals for secondary calibration and checking of optical temperature measuring equipment in high temperature systems. However, the final assessment will require additional accurate work on the same and other metals.

4. References

- [1] Cezairliyan, A., Radiance temperature of niobium at its melting point. *J. Res. Nat. Bur. Stand. (U.S.)*, **77A** (Phys. and Chem.), No. 3, 333-339 (May-June 1973).
- [2] Cezairliyan, A. and Righini, F., Measurement of melting point, radiance temperature (at the melting point), and electrical resistivity (above 2100 K) of zirconium by a pulse heating method. *Rev. Int. Hautes Tempér. et Réfract.* In press.
- [3] Cezairliyan, A., Coslovi, L., Righini, F., and Rosso, A., Radiance temperature of molybdenum at its melting point. *Proceedings of the European Conference on Temperature Measurement*. In press.
- [4] Foley, G. M., High-speed optical pyrometer. *Rev. Sci. Instr.*, **41**, No. 6, 827-834 (June 1970).
- [5] Cezairliyan, A., Morse, M. S., Berman, H. A., and Beckett, C. W., High-speed (subsecond) measurement of heat capacity, electrical resistivity, and thermal radiation properties of molybdenum in the range 1900-2800 K. *J. Res. Nat. Bur. Stand. (U.S.)*, **74A** (Phys. and Chem.), No. 1, 65-92 (Jan.-Feb. 1970).
- [6] Cezairliyan, A., Design and operational characteristics of a high-speed (millisecond) system for the measurement of thermophysical properties at high temperatures. *J. Res. Nat. Bur. Stand. (U.S.)*, **75C** (Eng. and Instr.), No. 1, 7-18 (Jan.-March 1971).
- [7] International Committee for Weights and Measures, The International Practical Temperature Scale of 1968. *Metrologia* **5**, No. 2, 35-44 (April 1969).
- [8] Bonnell, D. W., Traverton, J. A., Valerga, A. J., and Margrave, J. L., The emissivities of liquid metals at their fusion temperatures in *Temperature—Its Measurement and Control in Science and Industry*, H. H. Plumb, ed., Vol. 4, Part 1 (ISA, Pittsburgh, 1972), pp. 483-487.
- [9] Touloukian, Y. S. and DeWitt, D. P., *Thermal Radiative Properties*, Vol. 7 of *Thermophysical Properties of Matter* (IFI/Plenum, New York, 1970).
- [10] Cezairliyan, A. and McClure, J. L., Thermophysical measurements on iron above 1500 K using a transient (subsecond) technique. *J. Res. Nat. Bur. Stand. (U.S.)*, **78A** (Phys. and Chem.), No. 1, 1-4 (Jan.-Feb. 1974).
- [11] Bidwell, C. C., Radiation from solid and molten iron. *Phys. Rev.*, **3**, No. 6, 439-449 (1914).
- [12] Burgess, G. K. and Waltenberg, R. G., The emissivity of metals and oxides. *Nat. Bur. Stand. Bull.*, **11**, 591-605 (1915).

(Paper 79A4-856)